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A comparison between mesospheric wind measurements made near Christchurch (44°S, 173°E) using the high resolution doppler imager (HRDI) and a medium frequency (MF) radar

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Abstract. We report on the comparison of winds measured by a medium frequency (MF) radar near Christchurch, New Zealand, and by the high resolution doppler imager (HRDI). Previous comparisons have demonstrated that there can be significant differences in the winds obtained by the two techniques, and our results are no different. However, these data show relatively good agreement in the meridional direction, but large differences in the zonal direction, where the radar is regularly measuring the zonal wind as too easterly. To do the comparison, overpasses from the satellite must be obtained when it is close to the radar site. The radar data are averaged in time around the overpass because we know the radars sample phenomena which have spatial and temporal scales which make them invisible to HRDI. There are a limited number of overpass comparisons which limit our confidence in these results, but a detailed analysis of these data show that the proximity of the overpass is often an important factor in the differences obtained. Other factors examined include the influence of the local time of the overpass, and the amount of radar data averaged around the overpass time.

Key words: Atmospheric composition and structure (instruments and techniques) – Meteorology and atmospheric dynamics (middle atmosphere dynamics; instruments and techniques)

1 Introduction

Recently, much work has been done in comparative studies between winds obtained from the high resolution doppler imager (HRDI) instrument and those obtained from ground-based sites (e.g. Burrage *et al.*, 1996, 1993; Lieberman *et al.*, 1998; Khattatov *et al.*, 1996). Presented here are the results of the first full comparison between the HRDI winds and those located with the MF radar at Birdlings Flat (44°S, 173°E) near Christchurch, New Zealand.

We start with an examination of the geometrical issues which complicate comparisons of this sort, including a discussion of the process by which highly localised radar data are compared with satellite data. Various remote sensing issues are discussed and the notion of a satellite "overpass" (Khattatov *et al.*, 1996) is introduced.

Comparisons between 28 individual satellite measurements and relevant MF radar data are undertaken. The individual overpasses are binned according to proximity, local time and data rate and the results of the individual comparisons are discussed in light of these factors.

2 Comparing satellite and station data

Comparisons between satellite and station data are complicated by factors which involve the different sampling methods employed by the instruments. These factors include the different geometries of stations and satellites, the different sensing methods and various issues regarding the spatial and temporal binning of the data.

The Upper Atmosphere Research Satellite (UARS) which carries HRDI flies around the rotating Earth in an almost circular orbit at a height of 585 km (Burrage *et al.*, 1996). This gives the instruments aboard the satellite a good view of the world in terms of spatial coverage, but does not provide the high sampling rate that a ground station site can provide. As a result, features on time scales shorter than 95 min (the time it takes for one UARS orbit) are a problem for the instruments aboard UARS; HRDI and the other instruments aboard UARS essentially under-determine effects on short time scales.

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Similarly, because of the large horizontal distances over which instruments such as HRDI sample (see Fig. 1) features with small spatial scales can be hard to detect (Khattatov *et al.*, 1996). Even if small-scale phenomena are detected, the smoothing inherent in the reduction and inversion process can act to smear out these features (see later). This is borne out in most of the other comparative studies involving HRDI and MF radars, e.g. see Khattatov *et al.* (1996), or Burrage *et al.* (1996).

The situation is quite different for a ground station; short lived or small-scale features are observable by radar, but only in the immediate vicinity of the site. Because they only sample the atmosphere in the vertical, MF radar stations, such as that located at Birdlings Flat, are very good at gathering a near continuous picture of the atmosphere inside a volume above the site, but give no information about the state of the rest of the atmosphere.

To contrast the platforms, one might say that the advantage of a field station is that it gives a very good, nearly continuous record of the atmosphere directly above the site. The disadvantage is that spatial coverage is extremely limited. The advantage of a satellite platform is that it enables near global coverage of atmospheric phenomena. The disadvantage is that the temporal density of data at a given location is poor.

A second consideration to be taken into account is that the radar and satellite are not actually sampling the same physical quantity. While the radar signal is reflected by irregularities in the electron density profile with the resulting diffraction pattern being analysed to produce wind profiles, the satellite receives light (in the case of HRDI corresponding to various O_2 lines) scattered by a volume of atmosphere, see Burrage *et al.*, (1996). The lines are then reconstructed, corrected for the spacecraft velocity and finally a value for the radial velocity of the atmospheric scattering region is obtained.

Despite these differences in procedure, the radar and HRDI both detect wind as their primary *dynamical* quantity. Unlike winds derived from pressure or temperature-based satellite sensing instruments (for example, the PMR aboard Nimbus 6, Lawrence and Randel, 1996), wind is for HRDI a directly retrieved quantity, rather than something derived via the application of large-scale dynamics such as the geostrophic approximation. As a result, if the HRDI instrument viewing region traverses Birdlings Flat, a direct comparison can be made between the wind field as obtained by the MF radar and the wind field detected by the satellite as it flies by.

Following Burrage *et al.* (1996) and Khattatov *et al.* (1996) it was decided that the best way to go about this comparison was to compare the radar winds with the satellite winds at only those times when the satellite viewing region (see Fig. 1) passed ‘‘over’’ the radar site. Using this technique, it can be ensured that the satellite and radar are (however briefly) sampling the wind in the same region of atmosphere at the same time.

The question then arises ‘How close must a satellite overpass be to be considered ‘‘overhead’’?’ In order to answer this question one must make a trade-off between proximity and scarcity: ideally, the satellite viewing region would be considered only if it passed right over Birdlings Flat. Unfortunately, that is not a common occurrence, and such a requirement would be too strict, the net result would be that we would obtain very few data. (Birdlings Flat is about 5° too far south to be a latitude routinely visited by UARS. See Khattatov *et al.* (1996) for details.) The restriction is therefore relaxed and again following Burrage *et al.* (1993) and Khattatov *et al.* (1996), any overpass within 500 km of Birdlings Flat was deemed overhead. With this definition, 28 overpasses distributed roughly isotropically about Birdlings Flat were available for comparison.

Figure 2 displays a schematic geometry of an overpass. The satellite views a region of the atmosphere and deems all the effects on the recovered line shape to have come from the scattering region S. The MF radar senses

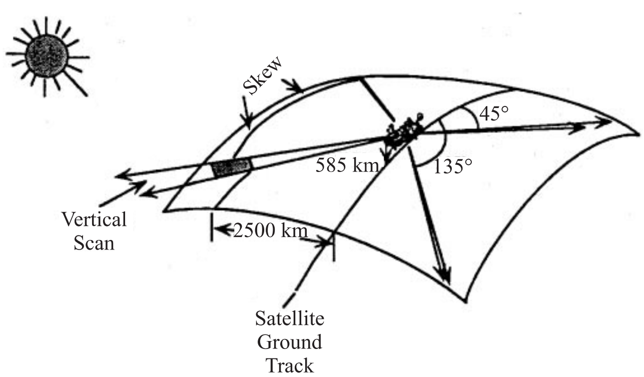

Fig. 1. HRDI viewing geometry (after Burrage *et al.* [1996]). The instrument obtains an observation in the shaded region, which is approximately 300 × 300 km in horizontal extent. The telescope is then slewed through 90 degrees as the spacecraft moves in the direction indicated. The instrument then takes another measurement (on the same side of the satellite track) of the same region of atmosphere. These measurements are then combined and a velocity obtained for the relevant region of atmosphere

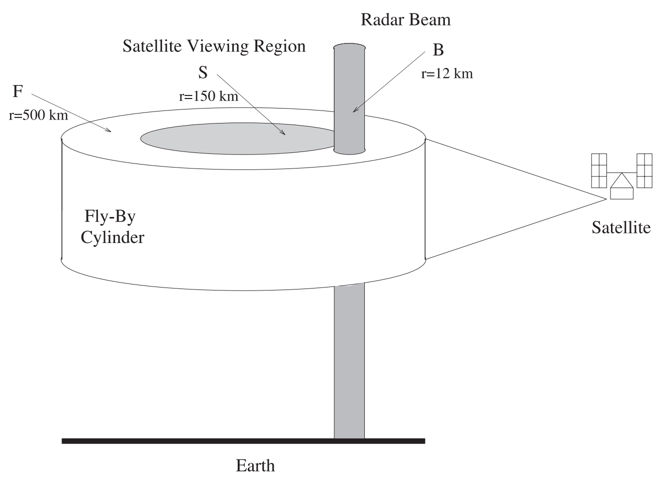

Fig. 2. Schematic diagram of an overpass. The satellite viewing region is represented by the cylinder S, the radar beam by the cylinder B and the outer limit of the overpass is denoted by the cylinder F. The radar beam B has to pass through the cylinder F for the observation to be considered an overpass

winds directly above Birdlings Flat (in the cylindrical region B). The cylinder F is the 500 km radius. The scattering region S must pass within F in order for the event to be considered an overpass. Of course, in reality, there is no sharp cut-off in the contributions to the measurements, and the radar measurement is probably more like a cone, with radius near 12 km at 80 km. Also, the HRDI region is not really a cylinder, this figure showing a simplified, conceptual representation of the overpass geometry. Although the width of the satellite viewing region is close to 300 km, the satellite wind can best be seen as a weighted average of the wind fields from all lines-of-sight which intersect with the various tangent altitudes making up a vertical profile. The weights taper off so that increasingly small contributions to the line shape are made by points further away from the center of the viewing region. The HRDI instrument is described in detail by Hays *et al.* (1993).

In the case of HRDI additional smoothing of the data arises because the raw along track data are smoothed to compensate for noise introduced in the inversion process. A consequence of this is the smearing out of small-scale atmospheric features. Since the MF radar monitors the atmosphere above a single point, no horizontal smoothing can be carried out for the radar winds. Both instruments have reasonably similar vertical resolution; in terms of the actual height resolution of the instrument, HRDI makes raw measurements every 2.5 km, while the distance between vertically independent measurements is roughly 4 km for the radar at Birdlings Flat.

The second aspect of the binning problem in this comparison is to know how long the radar should be sampling the atmosphere before and after an overpass. The satellite passes by at 7500 ms^{-1} building up a measurement from two 30-s samples 9 min apart, while the radar provides frequent effectively instantaneous but irregular sampling. Because of the spasmodic sampling rate, previous studies have found it difficult to use MF radar data to establish a reliable picture of the wind field on less than hourly timescales (e.g., Plagmann *et al.*, 1998).

Longer temporal baselines or time scales generate more reliable pictures of the average wind field throughout the time considered. However, if the temporal baseline of radar measurements is too long the snapshot as seen by HRDI will not be compared with something relevant, but with something like a daily average. The danger of letting the temporal baseline grow too long is especially notable in the case of the mid-latitude mesosphere around 80 km; in this region the dominant dynamical feature is the semi-diurnal tide (Andrews *et al.*, 1987). If this feature plays too significant a part in the radar data, then the average wind profile obtained by the radar will not adequately reflect the wind field (as would have been seen by the radar) at the time of the overpass, and this must result in poor agreement between the radar and HRDI.

Consequently, a happy medium must be found between short temporal baselines (which may be unreliable) and long temporal baselines (which may be too "smoothed"). Two attempts at solutions are considered in this study. The first is to stretch the baseline out both forwards and backwards in hourly steps from one hour to six hours either side of the overpass, and then to compare the various bins to find which, if any, are the optimal bin-widths. The second is to take 36 day means of both radar data and HRDI data. In this latter case, the average radar wind should be more reliable than the far shorter time scales considered above and the semidiurnal tidal effects on the HRDI wind should largely average out as the spacecraft precesses through all daylight times over that period.

3 Results

3.1 Seasonal comparisons

In this section we compare the instruments using the first of the two techniques described: each HRDI overpass was compared with corresponding wind data from the radar using time-bins which extended an integer number of hours either side of the overpass, from one hour either side to six hours either side. Three independent factors were examined in the process of these comparisons: (a) the time of day, (b) the proximity between the satellite sensing region and that of the radar site and (c) the number of data points used in the calculation of the radar wind. Factors (a) and (c) are not completely independent, as the radar signal is stronger during daylight hours. A priori we expect the third of these factors will determine to some extent the reliability of the Birdlings Flat radar measurement, more data generally implies more reliable wind estimates.

This method of binning the data has several advantages, most importantly in the comparisons between the rms differences between the data sets. Because each satellite overpass is compared with radar measurements made at essentially the same time, there should not be any tidal effects skewing either data set.

Using similar binning techniques, other authors (Gault *et al.*, 1996; Burrage *et al.*, 1996) have found that often there is not good agreement between satellite-borne Doppler measurements and MF radar data for individual overpasses, and so we have further binned the overpasses into seasonal bins for winter (May-July) 1993 and summer (December–February) 1993–94. Both the average and rms values of these seasonal agglomerations were examined.

The seasonal average winds are plotted in Figs. 3 and 4. Each of the curves in these plots refer to a particular time-bin width. Although the shortest time-bin width (1 h either side of the overpass) frequently gives the best agreement with the HRDI data it is also the most variable, being strongly dependent on a good data rate. The longest time-bin width, corresponding to a bin reaching six hours either side of the overpass, almost always shows poorer agreement with the HRDI data than data from any other bin, and this is consistent with the expected effects of tidal contamination. The local time of the observation, which corresponds to the phase

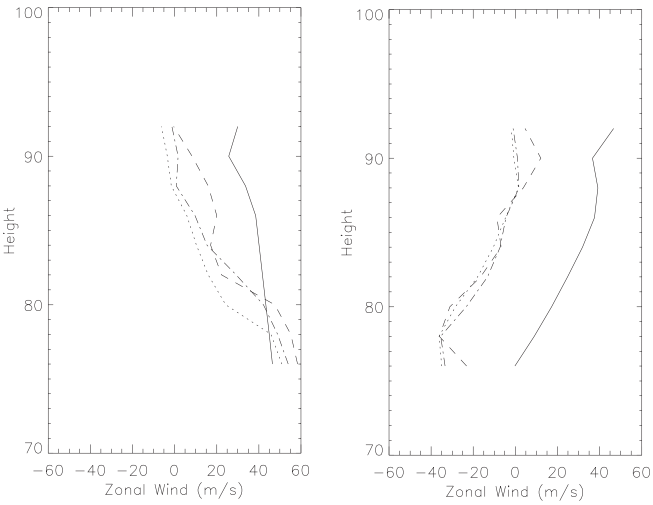

Fig. 3. "Seasonal" average of the zonal winds from winter (left hand panel) and summer (right hand panel). The solid line represents the HRDI data, the dashed line the two-hour bin, the dot-dashed line the six-hour bin and the dotted line the twelve-hour bin

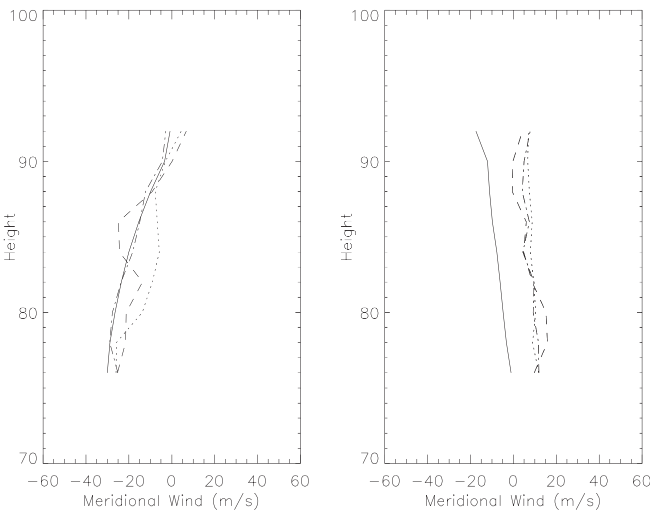

Fig. 4. As in Fig. 3, except for the meridional wind

of the tide at the time of the overpass, determines the extent to which the radar data is tidally smeared by both the diurnal and semi-diurnal tide. This is especially true of meridional winds, where the latitudinal gradients in the tides may be a problem for the large spatial sampling of the HRDI measurements (Burrage *et al.*, 1996).

For the zonal winds, there is good agreement at the low altitude end of the sampled range in winter, although this agreement diminishes with altitude. In summer the two data sets reveal similar vertical structure in the wind field but disagree by roughly 35 ms^{-1} throughout the range of measurements. However, despite the offset between the datasets in summer, both HRDI and the MF radar at Birdlings Flat record some similarities in the vertical structure in the wind field; in both data sets the wind becomes more westerly with height by about 35–40 ms^{-1} between 76 and 100 km. For the meridional winds, we see that the two-hour time bin has the most vertical structure, especially in winter, where the agreement between the two data sets is good. In summer there is some difference between the radar winds and those obtained from HRDI; HRDI observes a northerly wind field throughout the height range while the radar observes southerlies.

The systematic differences between the winds can also be seen when scatter plots are used to show the variance between the two sets of data as in Fig. 5. In this figure data from the six hour bin (three hours either side of the overpass) has been used to show the westerly bias in the zonal wind and southerly bias in the meridional wind. Because agreement varies with height no regression across the height range was attempted.

Burrage *et al.* (1996) discusses the possibility, raised by Manson *et al.* (1991) in the context of comparisons with mesospheric rocket soundings, that some MF radars need corrective factors applied to their wind measurements. Factors of up to 2.0 have been suggested (Manson and Meek, 1986) and although there are individual comparisons between HRDI and the MF

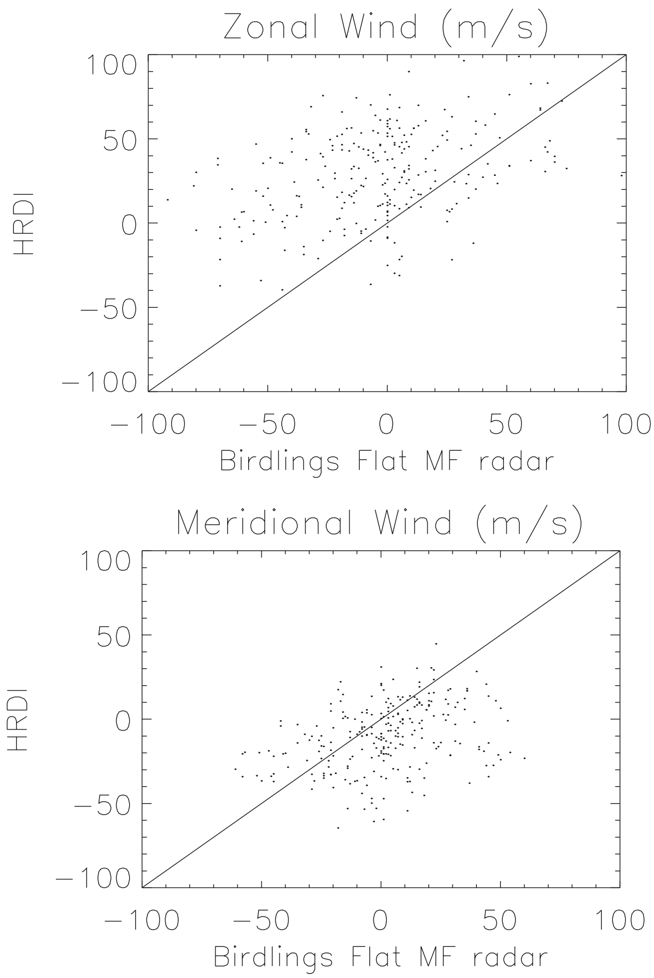

Fig. 5. A comparison of winds in the altitude range 76–92 km for both zonal and meridional winds for the 28 overpasses. These scatterplots include all the overpasses at *all* the examined heights. Note that because neither HRDI nor the radar actually take independent measurements every 2 km not all the points in the plots are independent

radar at Birdlings Flat that could be viewed as supporting this contention, a simple corrective factor would not explain many of the observed discrepancies between the data. In fact, Fig. 5 suggests, if anything, that there is a greater spread in the magnitudes of the radar winds than there is in the HRDI winds, quite a different result than that obtained by Khattatov *et al.* (1996) or Burrage *et al.* (1996).

Meridionally, the HRDI data agrees exceptionally well with the MF radar data in winter, especially with those data corresponding to the six-hour time-bin. In summer, HRDI records, on average, slightly more poleward winds than the MF radar does. The ambitious eye may detect a slight difference between the HRDI and the radar meridional winds, but it would be premature to conclude that this was indicative of any systematic offset. A majority of points lie beneath the $v_{HRDI} = v_{radar}$ line but they do not lie far beneath it. The difference between radar and HRDI winds in summer in the meridional direction is only around 10 ms^{-1}, and this difference is probably too small to suggest the presence of a systematic offset between the data sets given the small number of data points.

Like the other MF radars discussed in Burrage *et al.* (1996) and Khattatov *et al.* (1996), the Birdlings Flat radar detects more structure than the HRDI instrument does. This is not so noticeable when binned into the seasonal averages presented above, but some of the individual comparisons reveal it strikingly: Fig. 6 displays the winds for two overpasses from June 1993. In each of these cases considerably more vertical structure is apparent in the MF radar data than in the HRDI data.

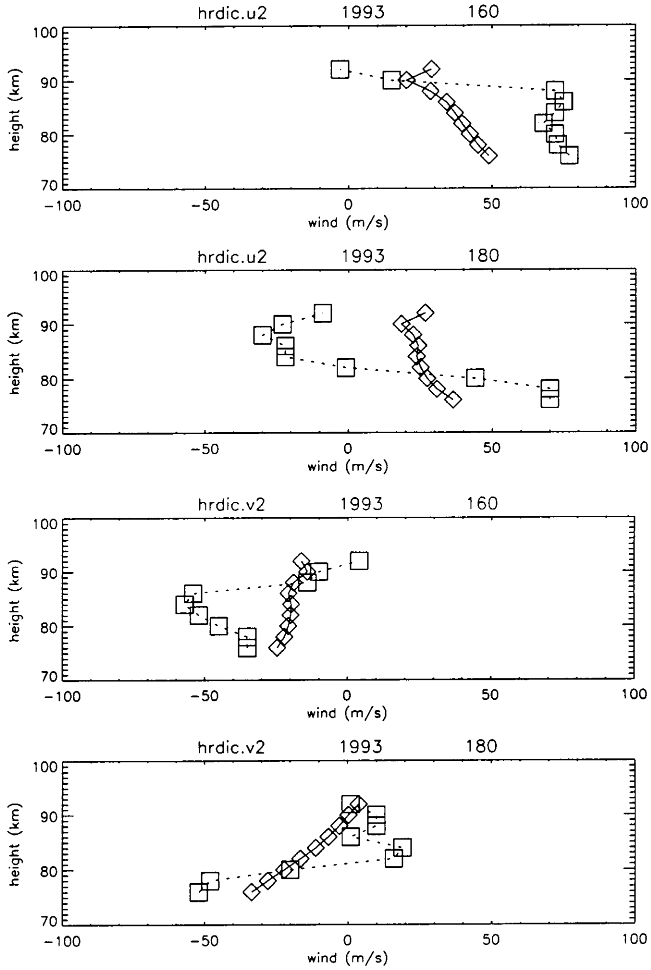

Fig. 6. Zonal winds (upper two panels) and Meridional winds (lower two panels) from two overpasses in June 1993. Radar winds from Birdlings Flat (squares) and HRDI (diamonds). The radar data has been integrated for a period of one hour either side of the time of the actual overpass

3.2 Sampling

To assess the effect of sampling, the 28 HRDI overpasses between May 1993 and March 1994 were sorted three ways; (a) with respect to local time, (b) with respect to number of radar data points and (c) with respect to proximity of the HRDI path. The overpasses are also tabulated according to these three variables in Table 1. For these comparisons, the six-hour bin-width was used.

3.2.1 Local time. Of the 28 HRDI overpasses, 15 occurred within three hours of the local solar meridian (around 0:30 UT). Those were compared with those which occurred more than 3 h from the meridian: rms differences between the HRDI winds and those obtained by the radar were compared by season and these results are displayed in Fig. 7.

Zonally, the near-noon data showed better agreement with HRDI than did the off-noon data at most heights during summer. The difference in agreement was not particularly large, although it was consistent. In winter, zonally, there was less consistent difference between the data sets; if anything the agreement between the off-noon data from the two instruments agreed better than did the data from the near noon hours.

During winter the meridional data from times close to local noon generally showed better agreement at most heights than did the data from off-noon hours, although the discrepancy between the two data sets varied somewhat with height; it was neither a consistent difference nor a large one. In summer there was even less difference between the near-noon and off-noon data in the meridional direction. Because rms differences between data sets were comparatively small in this group, no systematic difference can be clearly isolated.

3.2.2 Proximity. The radius of the cylinder F in Fig. 2 was halved, thereby effectively halving the number of overpasses according to the definition made already. The data were again binned according to seasons and then compared so that the HRDI versus radar winds for those overpasses within 250 km of the radar site (14 overpasses) were compared with those HRDI and radar winds for those overpasses in the range 250–500 km (14 overpasses). We call data from the close passes, "proximate" data, that is data which lies within

Table 1. HRDI overpasses, 1993–94. The date of each overpass is indicated, along with an indicator as to whether or not is "close" in space, near noon, and/or well sampled. See text for details

Year	Day	Hour	Minute	Close	Noon	Sampling
1993	149	2	9	+	−	+
1993	156	23	18	+	+	−
1993	160	21	52	−	+	+
1993	176	3	47	−	−	+
1993	180	2	22	−	+	−
1993	184	0	58	+	+	−
1993	188	23	35	−	+	−
1993	315	18	24	+	−	−
1993	334	23	4	−	+	+
1993	338	21	40	+	+	+
1993	342	20	17	+	−	+
1993	346	18	53	+	−	+
1993	353	5	58	+	−	−
1993	358	4	39	−	−	+
1994	1	1	50	+	+	−
1994	8	23	2	+	+	−
1994	12	21	39	−	+	+
1994	15	2	46	−	+	−
1994	17	20	17	+	−	+
1994	18	1	18	−	+	−
1994	18	6	19	−	−	−
1994	20	18	49	−	−	−
1994	23	4	59	+	−	+
1994	25	22	29	−	+	+
1994	32	2	14	+	+	−
1994	40	23	30	−	+	−
1994	48	20	42	−	−	−
1994	72	2	13	+	−	−

the cylinder S in Fig. 2. Data from the outlying cylinder F (but not inside S) are called "non-proximate".

As can be seen from Fig. 8, it was found that those data corresponding to more proximate overpasses were in slightly better agreement than those data where the HRDI sensing region was further away from the radar site, more so in winter than summer.

Generally, the data from the more proximate overpasses exhibited lower rms differences between the MF radar and HRDI data sets than did the data from less proximate overpasses. There are of course exceptions to this but in all cases where there is a clear disparity in the rms differences, the more proximate data agrees more closely with the HRDI data than the less proximate data. This difference manifests itself in all four plots presented in Fig. 8; most clearly in the summer zonal below 82 km, in the winter zonal above 84 km, in the summer meridional above 85 km and in the winter meridional below about 80 km.

3.2.3 Data rate. The third variable considered was the number of points per radar wind estimate for each overpass. For a given temporal bin-width a wind estimate at a particular height was made up of a number of different direct radar wind measurements, the number of which varied with height as the radar samples more often above 80 km than below 80 km.

For the 28 HRDI overpasses an average number of contributory data points per radar wind measurement was determined at each height. If the number of data points per radar wind value was greater than this average then the corresponding wind record was considered well sampled. If the number of data points per radar wind value was lower than the average then the corresponding wind record was considered more poorly sampled.

The "well" and "poorly" sampled bins were compared in terms of the rms difference between the HRDI and radar wind estimates, and the results displayed in Fig. 9.

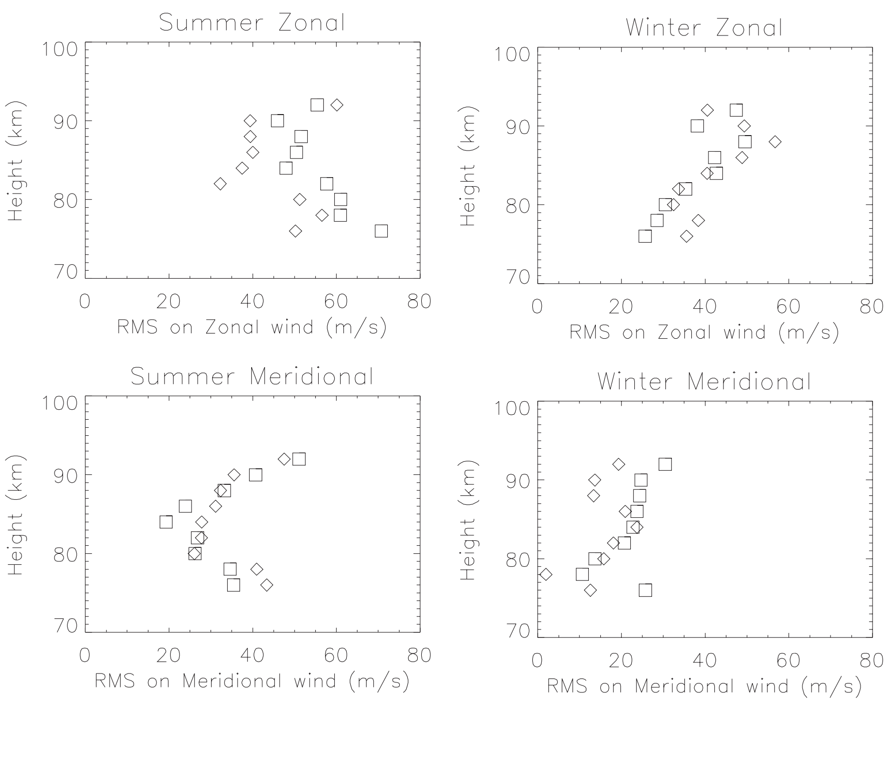

Fig. 7. RMS differences between the winds separated into data obtained less than three hours from the local noon (diamonds) and data obtained more than three hours from the local noon (squares)

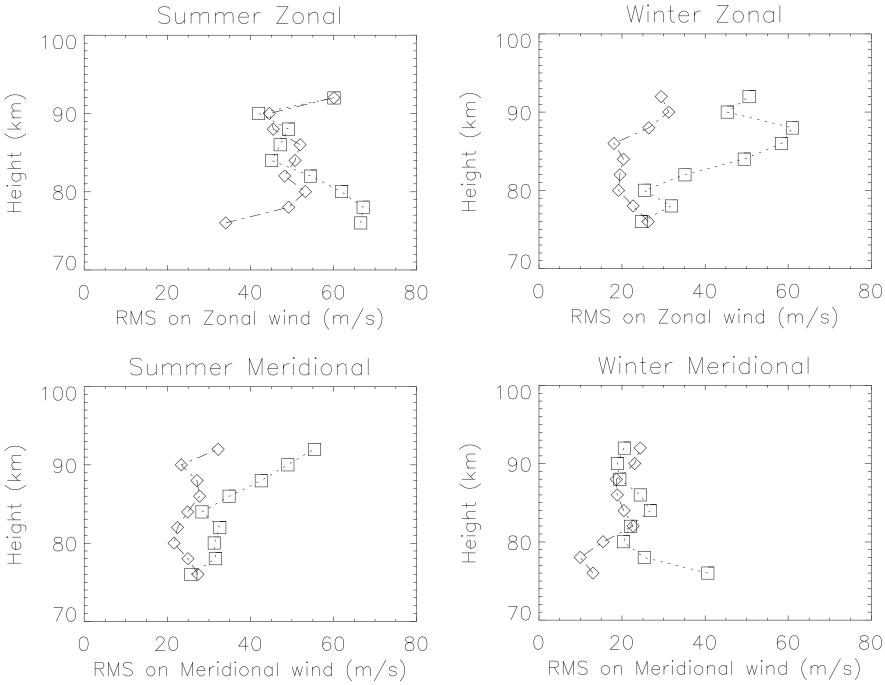

Fig. 8. RMS differences between data obtained during overpasses less than 250 km from the radar site (diamonds) and data corresponding to overpasses which were more than 250 km from the radar site (squares)

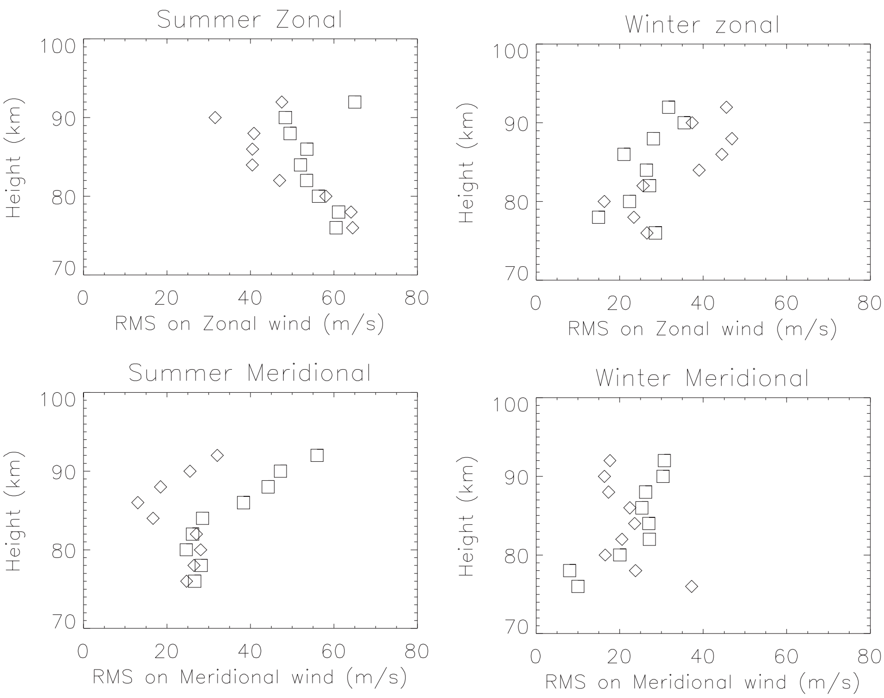

Fig. 9. RMS differences between data which had more than the average number of contributory wind measurements for the six hour time-bin (diamonds) and data which had less than the average number of contributory wind measurements for the six hour time bin (squares)

In winter, the zonal wind data showed little variation between well and poorly sampled data sets below about 84 km. Above this height, the poorly sampled data actually agreed better than the well-sampled data. The summer data is reasonably consistent in both the zonal and meridional directions; the well- and poorly sampled data are comparable in their rms errors up to about 82 km. Above this height the well-sampled data agree better with the HRDI data than do the poorly sampled data.

3.3 Thirty-six day comparisons

Because of the rate at which its orbit precesses over the spinning earth, HRDI samples 24 h of local time every 36 days, however complete altitude profiles are only taken during local daylight. This means that an average over that period will effectively smooth out semi-diurnal tidal components in the HRDI data, and additionally, will also smooth fast temporaral fluctuations which might be resolved by individual radar measurements.

In this section, we remove the longitudinal restriction in the overpass approach and use data from all longitudes sampled within a few hundred kilometres of 44S. These data were binned together and averaged over a period of 36 days. Similarly, the radar data for the same period were binned into a 36 day average. The 36 day period in question began on January 1, 1994. This start date was chosen because, in the 36 days from that date, eight separate overpasses occur. We are not aware of any bias in our results arising from the presence of the 2-day wave which was weaker in 1994 than some years.

Inherent in this sort of comparison is the assumption that the tides maintain their structure throughout the period of satellite precession. In other words, this sort of comparison relies on the tides being constant over the 36 days it takes the UARS satellite to precess through one solar day of local time.

Another factor possibly inhibiting the agreement between HRDI and the radar is HRDI's poor night visibility; aside from a thin region near 95 km, HRDI is blind at night. While the satellite is precessing its way through the night hours (local time) it is (effectively) not seeing the atmosphere. At a mid-latitude site such as Christchurch, this effectively means that HRDI cannot sample the six or seven hours of (local time) darkness.

The results of the comparison between 36 days of HRDI data and the same 36 days of radar data are displayed in Fig. 10. Zonally, it can be seen that, as with much of the overpass data, there is better agreement at lower altitudes ($\approx$80 km) than at higher altitudes, where the radar records little or no wind, while the satellite records increasing easterlies.

The zonal comparison using the "36 day" method shows similar results to the "seasonal" method discussed already. However, there is a considerable vertical gradient in the difference between the two sets of zonal wind which is not apparent in the "seasonal" comparison. As a consequence, while the 36 day HRDI average exhibits a steep vertical shear in the wind, characteristic of the transition from the mesospheric circulation to thermospheric circulation in this region, the MF radar measurements have the zonal wind dying away completely above about 85 km.

Meridionally, the agreement is exceptionally good, although with a mean meridional wind of around 0 ms^{-1} through the region considered, this agreement is perhaps less exceptional than it would have been if the amplitude of the wind was a large positive or negative number. Nevertheless, the meridional agreement using the 36 day method is probably the best agreement between the two data sets obtained by any method of binning the data. This implies, if nothing else, a strong degree of tidal stability over the period considered, especially given that tidal effects are normally most pronounced in the meridional direction (Andrews *et al.*, 1987).

Below about 85 km it would appear that these results are very consistent with those in the "seasonal" comparison, insofar that there is a systematic difference in the summer zonal winds and the meridional winds are in good agreement. It is not clear what interpretation should be given above 85 km, as will be discussed later.

4 Discussion

From the three analyses conducted it appears that both proximity and data rate do affect the quality of the agreement between the Birdlings Flat MF radar data and data obtained from the HRDI instrument. In most cases considered, wind data which were generated from a large number of measurements agreed well with HRDI observations. Similarly, the agreement between data sets was at its best when the HRDI viewing region passed closely over the region viewed by the MF radar.

The local hour of the overpass did not appear significant in this comparative study, unlike Khattatov *et al.* (1997a, b). It is possible that the choice of data window, being open for six hours, allowed sufficient tidal contamination to degrade the agreement between data sets.

Because proximity seems to be an important factor, and given that here the definition of proximity is a difference in location of a few hundred kilometres it would seem that near Birdlings Flat, there are large-scale wind variations on such horizontal scales. Such variations could be more prevalent in winter.

Although there was also support for data rate improving the agreement, the surprising result obtained for the winter zonal wind was that the data rate did not improve the agreement between the measurements. There are two obvious explanations for this: either this is simply the consequence of the statistics of small samples, or it results from the fact that getting more data meant more sampling from small-scale features which were stable enough in either time or space to cause differences from the HRDI measurements.

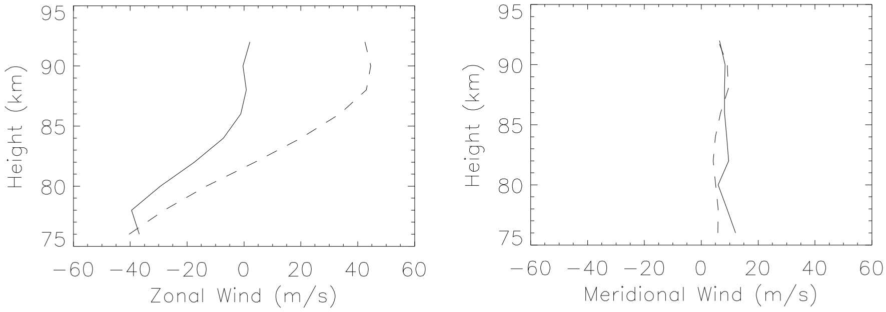

Fig. 10. Thirty six day averages of HRDI (dashed) and Birdlings Flat radar (solid) winds from early 1994

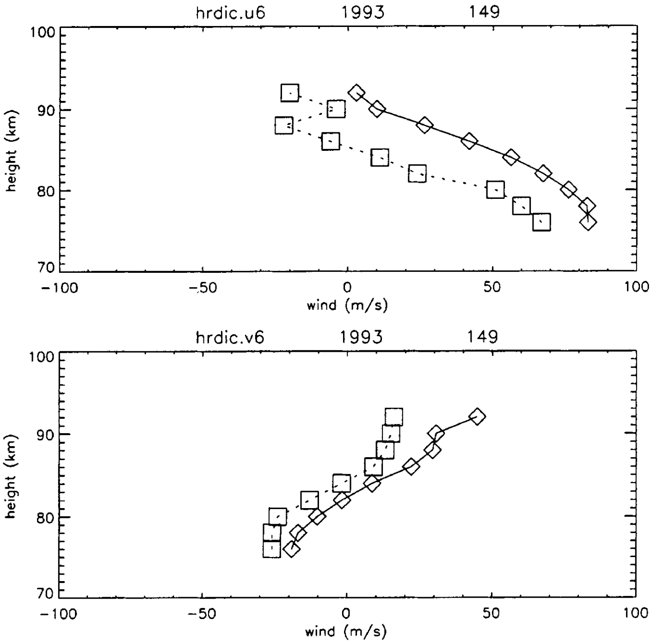

Fig. 11. Wind profiles for the individual overpass occurring on 29 May 1993: zonal wind (upper panel), meridional wind (lower panel). HRDI diamonds, radar squares

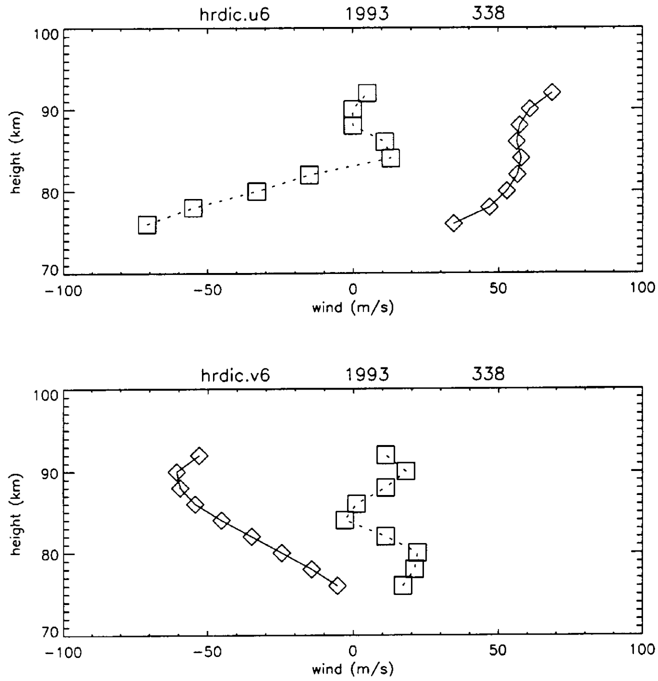

Fig. 12. Wind profiles for the individual overpass occurring on 3 December 1993: Zonal wind (upper panel), meridional wind (lower panel). HRDI diamonds, radar squares

Clearly none of these factors dominates the others to the extent that the rms differences between the two data types is significantly diminished by separating the overpasses into relevantly chosen bins: there is no consistent, systematic domination by one variable in all seasons and directions.

The situation is complicated by the unfortunate fact that very few of the data are both "proximate" and "well-sampled" as defined in the earlier comparison. Only four such overpasses exist. Although the well-sampled, proximate overpasses do not always seem to display significantly better agreement than the other data, it should be noted that the best single overpass (in terms of the agreement between the satellite wind field and the radar wind field) is both well-sampled and proximate: 29 May 1993 (Fig. 11). This overpass reflected the generally better winter-time agreement between HRDI and the radar.

There is only one overpass which is proximate, well-sampled and within three hours of the local noon. This is the overpass displayed in Fig. 12. It can be seen that this figure is quite similar to the seasonal mean picture in that the Birdlings Flat radar data broadly show the same structure as the HRDI data (albeit with a steeper vertical gradient with height below about 84 km). However, the two data sets are offset by a considerable margin. As usual, the HRDI data show a more westerly wind than the radar does. In the meridional direction the two data sets show quite good agreement at the lower heights but above about 84 km the HRDI data becomes increasingly northerly with height while the Birdlings Flat radar data shows some vertical structure around a mean southerly wind of around 15 m s^{-1}.

Generally, given the small sample size and the spatial and temporal aspects of the geometry of the comparison problem, the data fit the expected picture reasonably well. In comparison with the radar, HRDI is taking a large-scale snapshot of the atmosphere and it is found that the agreement between HRDI and the radar fades if the satellite viewing region is more than a few hundred kilometres from the radar site. It is also found that the reliability of the radar wind, in terms of the number of contributory data points, plays a role in the quality of the comparison as well.

The agreement between HRDI and the Birdlings Flat radar was often found to be best when the data window was only open an hour either side of the overpass. However, such short time-bin widths were also highly variable. Agreement with the HRDI snapshot did not generally degrade significantly until the time-bin extended out to at least four hours either side of the actual overpass. The radar exhibited its poorest agreement when the time-bin was left open for six hours either side of the overpass, in that case significant tidal effects would have been driving the atmosphere away from the overpass state while the data window was open.

The effect of some tidal effects was minimised by the comparisons carried out in Sect. 3.3. In that case, the good meridional wind comparison indicated that the tides were relatively stable on the quasi-monthly period used here. However, the zonal wind comparison produced results which are difficult to understand in the context of the results presented earlier. It is possible that a significant diurnal tide could have affected these results, but we believe the typical amplitude and phase of the diurnal tide above Birdlings Flat make this very unlikely.

At present it is not known what causes the apparent offset between the HRDI winds and those obtained at Birdlings Flat, or even if the offset is real. Only 28 overpasses are considered here and that is too small a number from which to conclude absolutely that there is a systematic zonal offset between the Birdlings Flat radar and HRDI. However, assuming that it is real, one needs to look for reasons for systematic offsets between the winds measured. As part of the explanation we need to explain why there is such a difference between the seasons in the zonal wind below about 85 km.

Apart from unexpectedly large tidal effects, one can come up with at least five classes of potential explanations as to why there might be systematic offsets between the HRDI measurements and the Birdlings Flat MF radar measurements. In brief these could be the influence of height determination, the influence of the receiving array geometry, the influence of gravity waves, errors in the HRDI winds themselves, and the nature of the sampling used.

The first of these potential explanations is that of McLandress *et al.* (1996) who found that the agreement between HRDI and WINDII improved when HRDI was shifted upwards (or WINDII downwards) by about a kilometre. However, in the case of the data being considered here, a shift of this scale is not sufficient to substantially reduce the discrepancy between the Birdlings Flat radar and HRDI data.

The second explanation could be that the right-angled triangle nature of the Birdlings Flat receiving array may bias the MF wind measurement. It is generally accepted that the optimal shape for an atmospheric MF radar is an equilateral triangle, while the Birdlings Flat radar is configured in a right-angled array. This may lead to different measurements along the hypotenuse and at right-angles to it. However, this would not account for the observed bias in this case as it does not explain why the MF radar would record zonal winds as being more easterly than HRDI because the right-angled effect would not distinguish between patterns blowing from east to west across the site and patterns blowing from west to east.

The third explanation involves the influence of gravity waves. Such gravity waves could be involved in two different ways. In the simplest, the waves clearly affect the nature of the turbulence in the region of interest. The MF radar technique relies on the full-correlation technique (e.g. Briggs, 1984), and it is possible that the assumptions in that procedure could be violated in a way that could bias the measurements (particularly averages, if some magnitude selectivity was involved).

It is also possible that the Southern Alps, which lie just to the west of the radar site, act to generate gravity waves which might be preferentially aligned in the zonal direction. Such waves propagating systematically in one direction could influence the measurements by propagating vertically and causing local distortions to the mean flow which are simply too local in position to be measured by the coarse horizontal averaging of the HRDI instrument, but which would be amenable to the MF technique. The vertical structure of such gravity wave effects is difficult to predict, but it could in principle explain the vertical structure of the biases seen between the two techniques. The fact that the proximity (Sect. 3.2.2) was more important in winter than summer is consistent with this explanation, as orographic waves are more likely to propagate to mesospheric heights in winter than in summer.

A fourth class of explanation involves the possibility that there was something wrong with these HRDI measurements. Clearly the HRDI instrument itself could have systematic errors which could also contribute to differences between the radar and the satellite winds. In particular, the zero wind determination which involved measurements from both sides of the spacecraft at the same spatial and local time locations (Burrage *et al.*, 1997) could lead to errors, even though it is believed to be more accurate than previous methods. There must also be questions over the particular HRDI soundings used here: a comparison of Figs. 3 and 10 with the HRDI climatology of Fleming *et al.* (1996) shows marked discrepancies between the summer mean zonal winds from our summer mean and the climatological January means from Fleming *et al.* (1996). In fact, the radar winds compare better with the HRDI climatology than does our sample of the HRDI winds!

The final potential explanation is the most unsatisfactory: that the time and spatial scales of the two techniques are so different, and the amount of data so little, that these results simply arise somehow from the sampling.

5 Summary

Data obtained from the MF radar at Birdlings Flat have been compared with data from the HRDI instrument aboard UARS. In keeping with the approaches taken by Burrage *et al.* (1993, 1996) and Khattatov *et al.* (1996), the MF radar data were binned into short time-bins either side of a HRDI overpass. Twenty-eight such overpasses were used in this comparison, and although any conclusions drawn from such a small number of data must be tentative, some features appeared consistently enough to warrant comment.

When compared, seasonal averages of the overpass radar data set gave consistently more easterly winds than the satellite data set in both summer and winter. Such a result is different from those presented in Burrage *et al.* (1996) in a comparison between HRDI and a number of other radar sites. The reasons for this are not immediately obvious. No bias is evident in the comparison of Plagmann *et al.* (1998), who compared meridional meteor winds, Fabry Perot winds and MF radar winds. However that work did not concentrate on the longer period comparison between the wind measurements. Work is underway on continuing that comparison between techniques, and extending it to the zonal winds.

In an examination of the reasons for the differences presented here, the overpasses were sub-sampled into comparisons which minimised the effects of tides (near local noon measurements), comparisons which examined the effects of proximity, and comparisons which examined the effect of data rate.

Unlike previous work (Khattatov *et al.*, 1997a), the local hour of the overpass did not appear to be a significant factor in the disagreement. However, both proximity and data rate did seem to be significant. The more proximate data generally produced lower rms values in both winter and summer, zonally and meridionally. Higher data rates also seemed to provide better agreement than low data rates, while the local hour of observation did not appear to have much influence on the rms differences.

When the time-bin is left open for six hours either side of the overpass the agreement was noticeably poorer than for shorter time-bins; leaving the data window open for that amount of time probably invites a significant tidal contribution which serves to degrade agreement between the data sets.

Thirty-six days of HRDI data were averaged and compared with an average of the radar data for the same period. Zonally, agreement was satisfactory at the lowest heights studied, but, as with the seasonally-binned overpass comparisons, agreement worsened with height. The HRDI data exhibited a considerably stronger vertical shear than did the Birdlings Flat radar data. Meridionally, the agreement achieved via this method was very good.

Overall, the agreement between the HRDI data and the winds obtained from the Birdlings Flat radar is probably a good example of the point made by Burrage *et al.* (1996) "Only when dynamical conditions are stable enough with a relatively small degree of high-frequency geophysical activity will a spatially localized measurement be representative of the large horizontal scales sampled by HRDI."

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